René Magritte, The Embellishment, 1962

Understanding the spread of climate sensitivity and cloud responses in CMIP6 models

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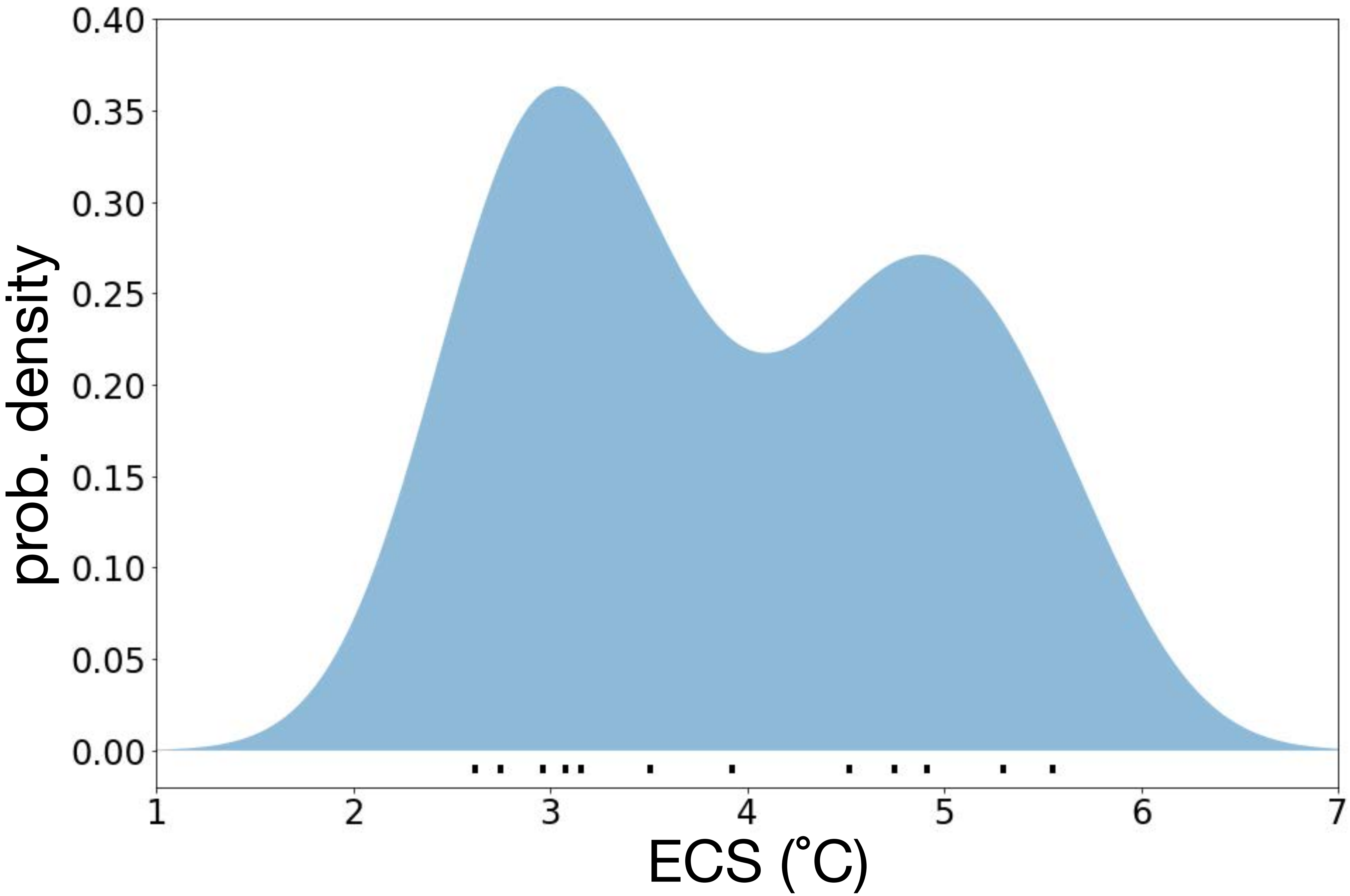
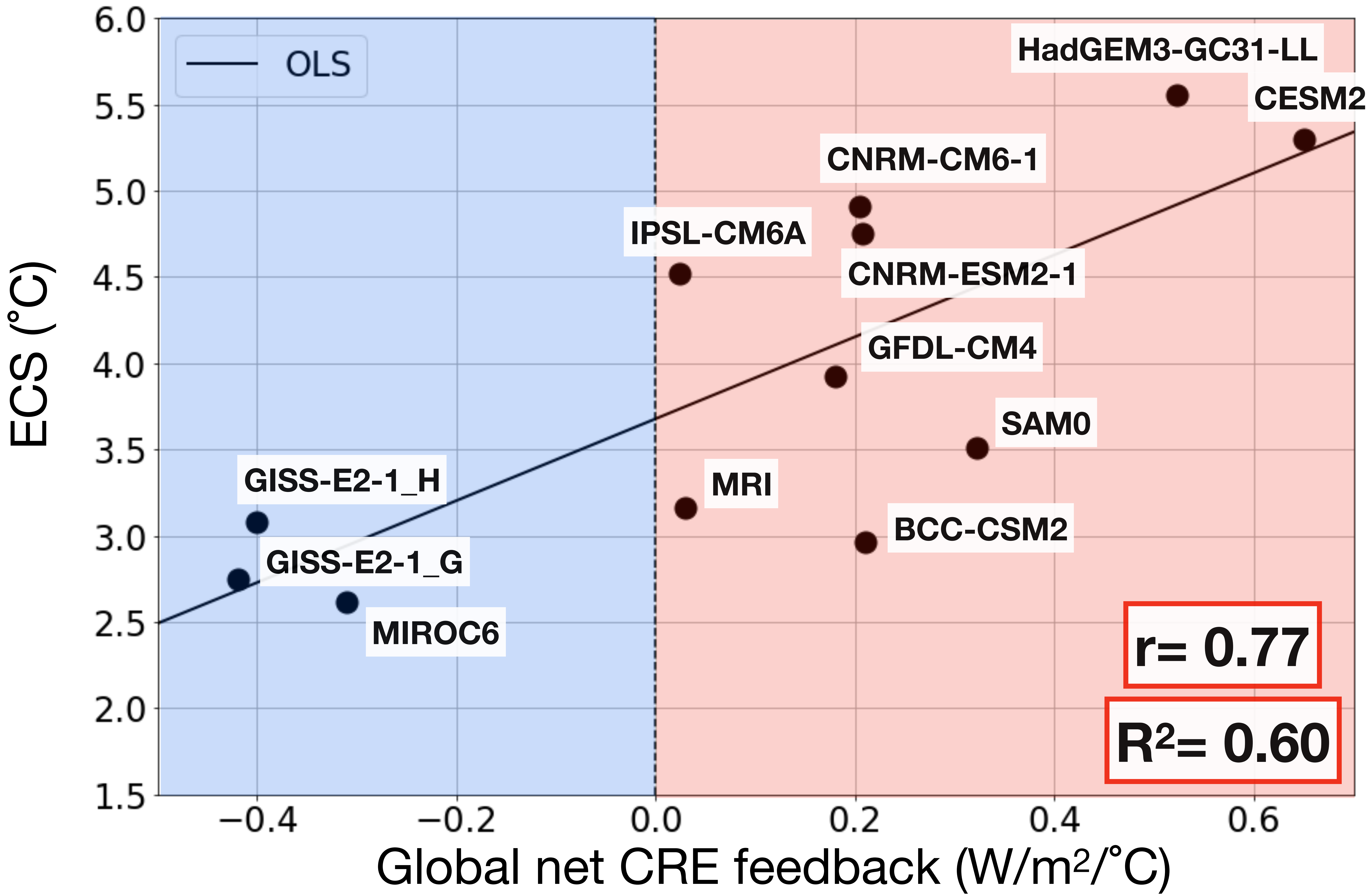
A more bimodal ECS distribution in CMIP6?

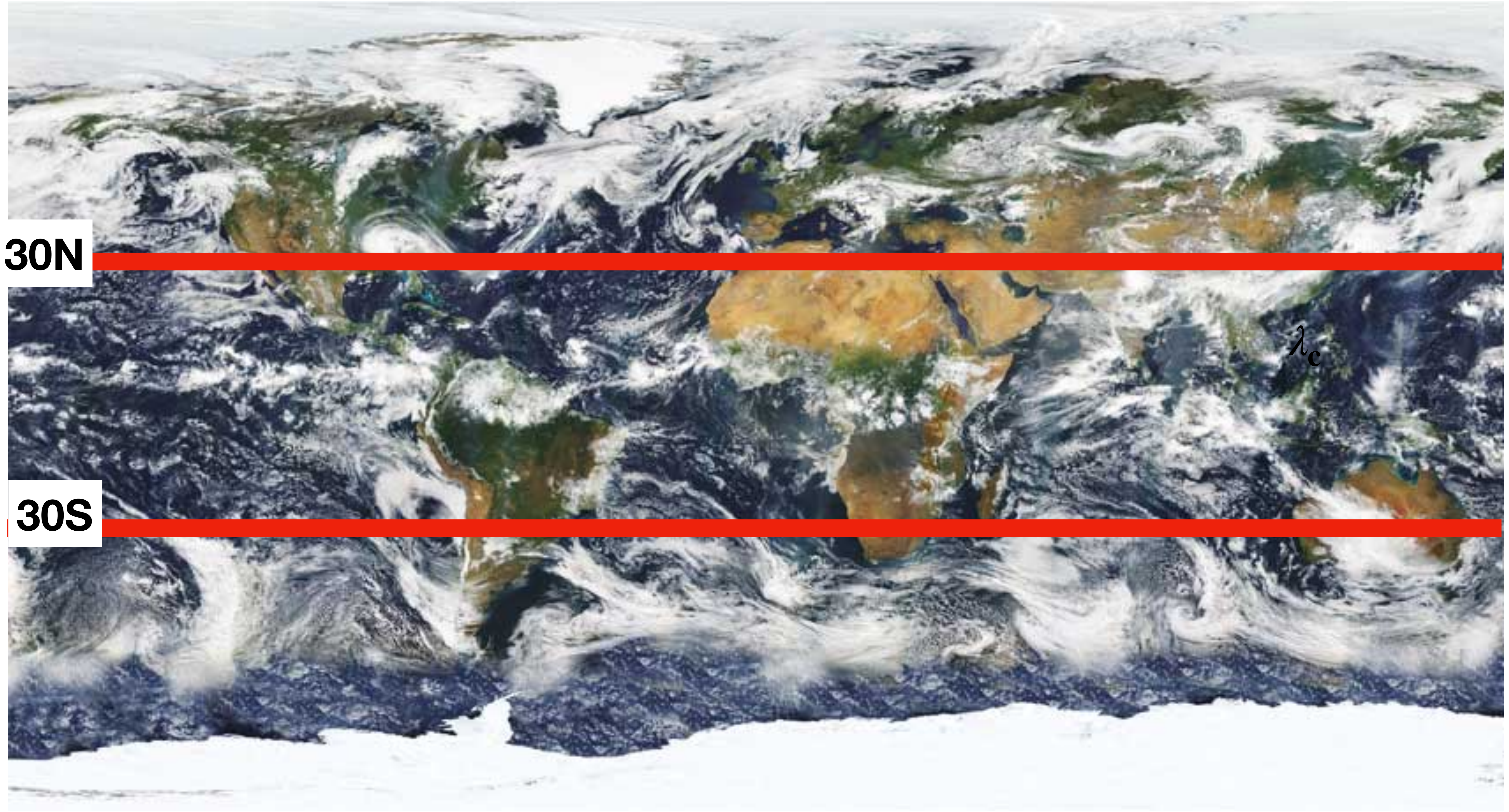


- ECS values calculated with Gregory regression (2004)
- CMIP6 range [2.6 - 5.6K] , mean 4K
- CMIP5 range [2.1 - 4.7K], mean ~3K (Andrews et al, 2012)
- Not spanning possible ECS range due to feedback and forcing compensations (Huybers 2010), and under-explored parameter spaces (Stainforth et al, 2005)

In CMIP6, spread in ECS still largely driven by varying cloud responses



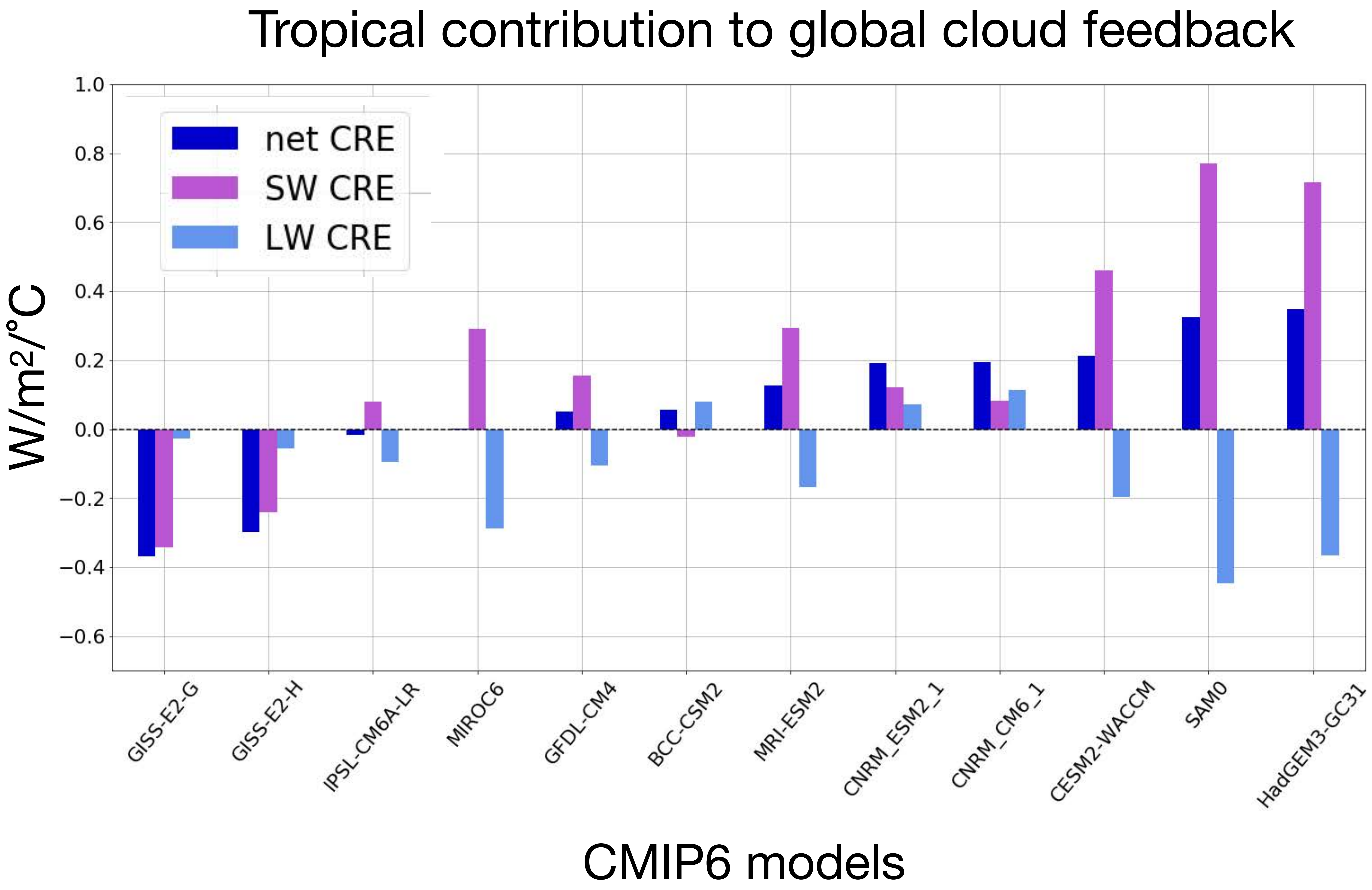
Tropical CRE variability can largely explain global CRE variability



NASA MODIS image of cloud cover

r (R^2)	ECS	Global CRE	Extra-tropical CRE	Tropical CRE
ECS	1	0.77 (60%)	0.43 (19%)	0.73 (54%)
Global CRE		1	0.55 (31%)	0.87 (76%)
Extra-tropical CRE			1	0.27 (8%)
Tropical CRE				1

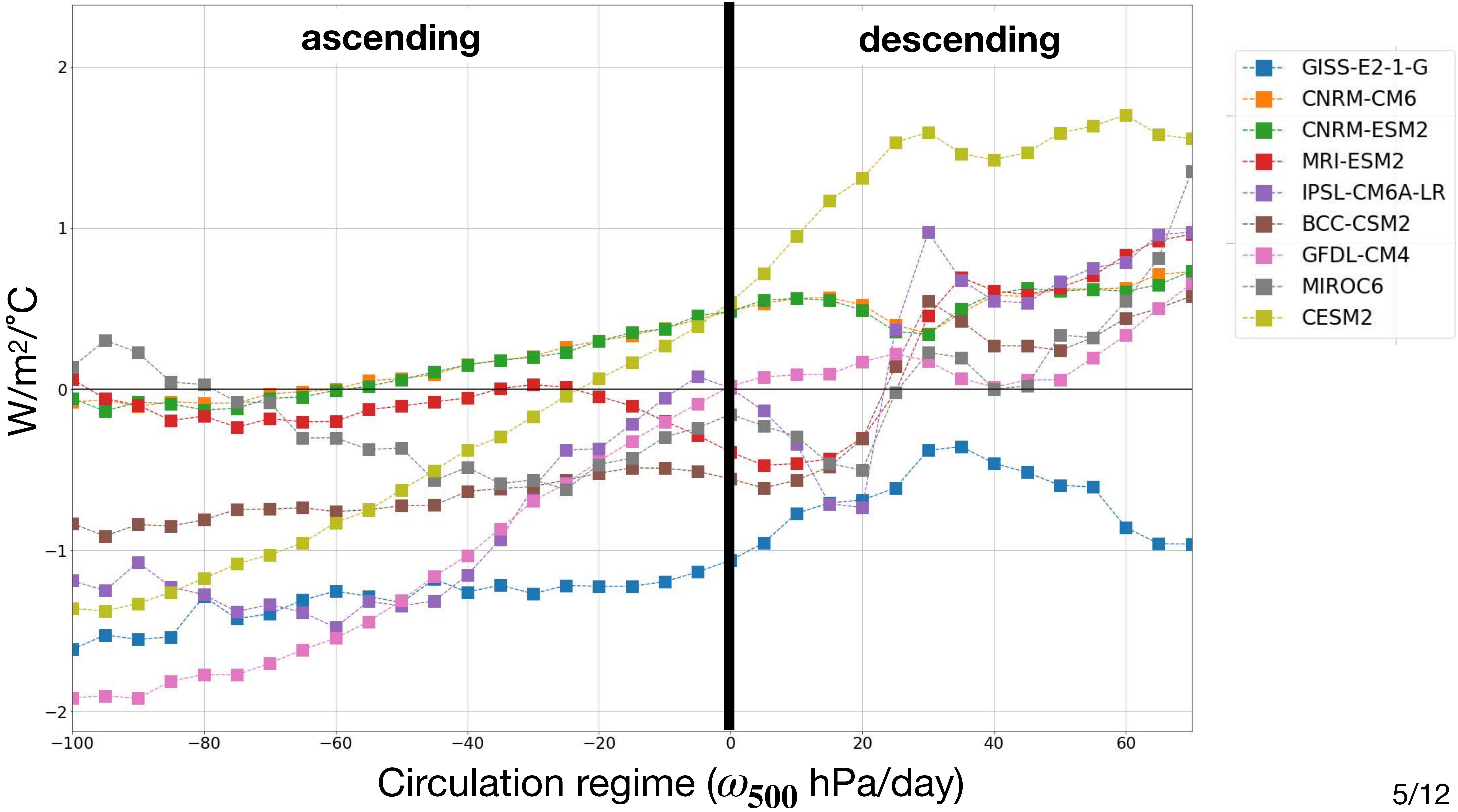
Tropical SW and LW CRE strongly anticorrelated



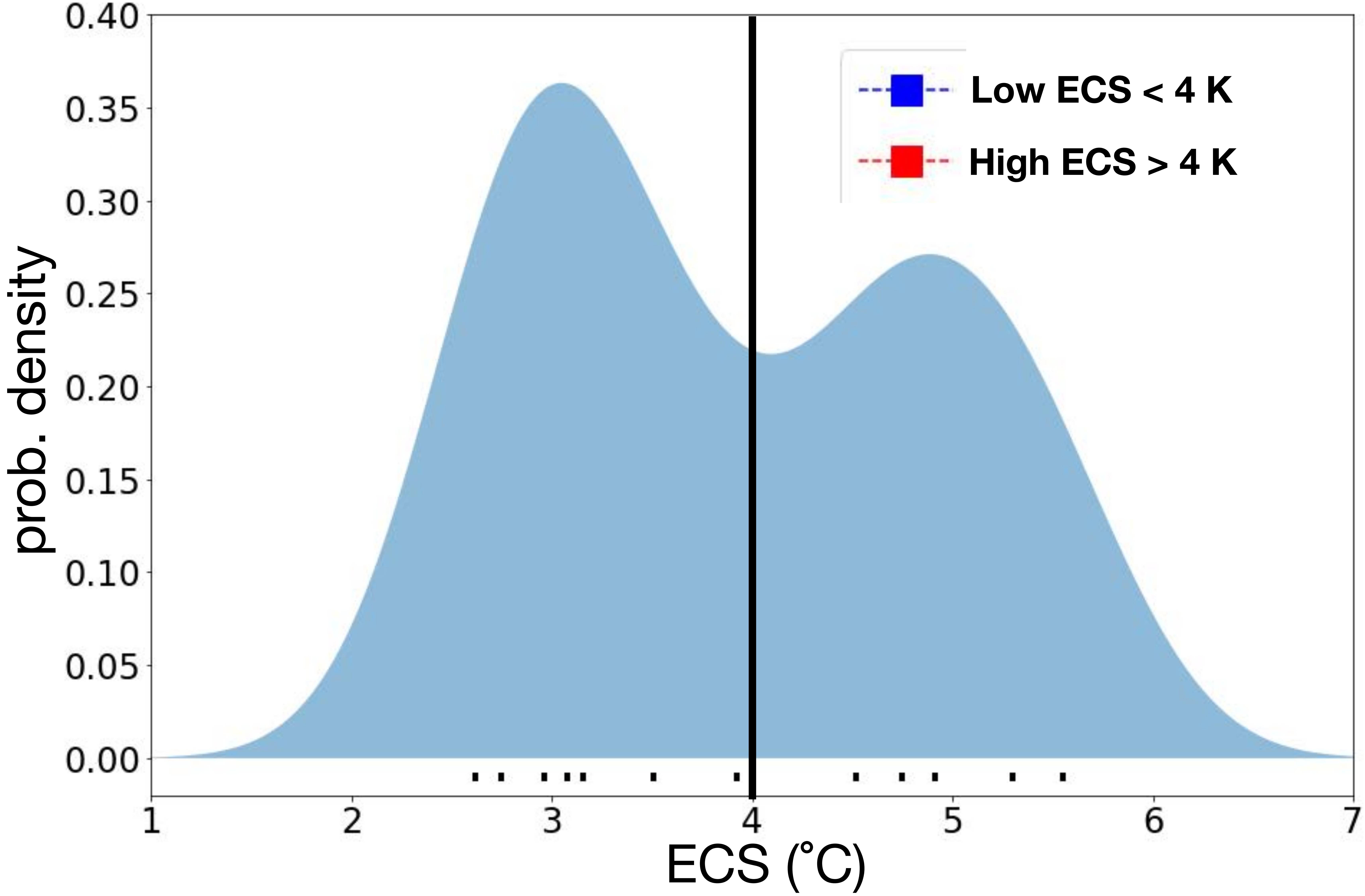
r (R^2)	Net CRE	SW CRE	LW CRE
Net CRE	1	0.87 (76%)	-0.40 (16%)
SW CRE		1	-0.80 (63%)
LW CRE			1

Which dynamical regimes are contributing to the spread in CRE?

$\overline{\text{Y150}}$ - $\overline{\text{piControl}}$



Stratify cloud feedbacks by low and high sensitivity models



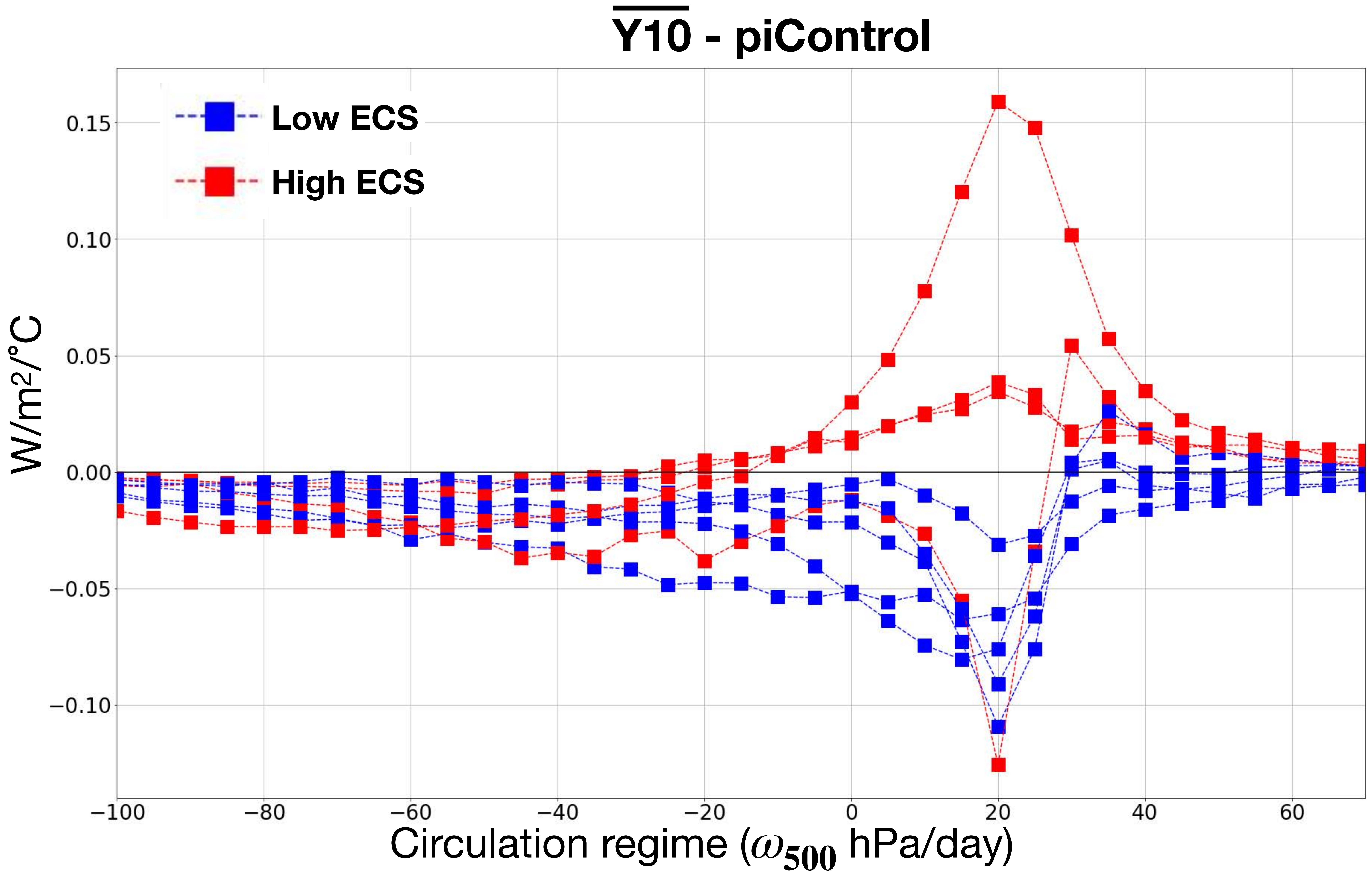
Low sensitivity

ECS < 4 ˚C
[GISS-E2-G, GISS-E2-H, MIROC6, MRI-ESM2, BCC-CSM2, SAM0, GFDL-CM4]

High sensitivity

ECS > 4 ˚C
[CNRM-CM6, CNRM-ESM, IPSL-CM6A, HadGEM3, CESM2]

Strongest divergence of early cloud feedback in subsidence regimes

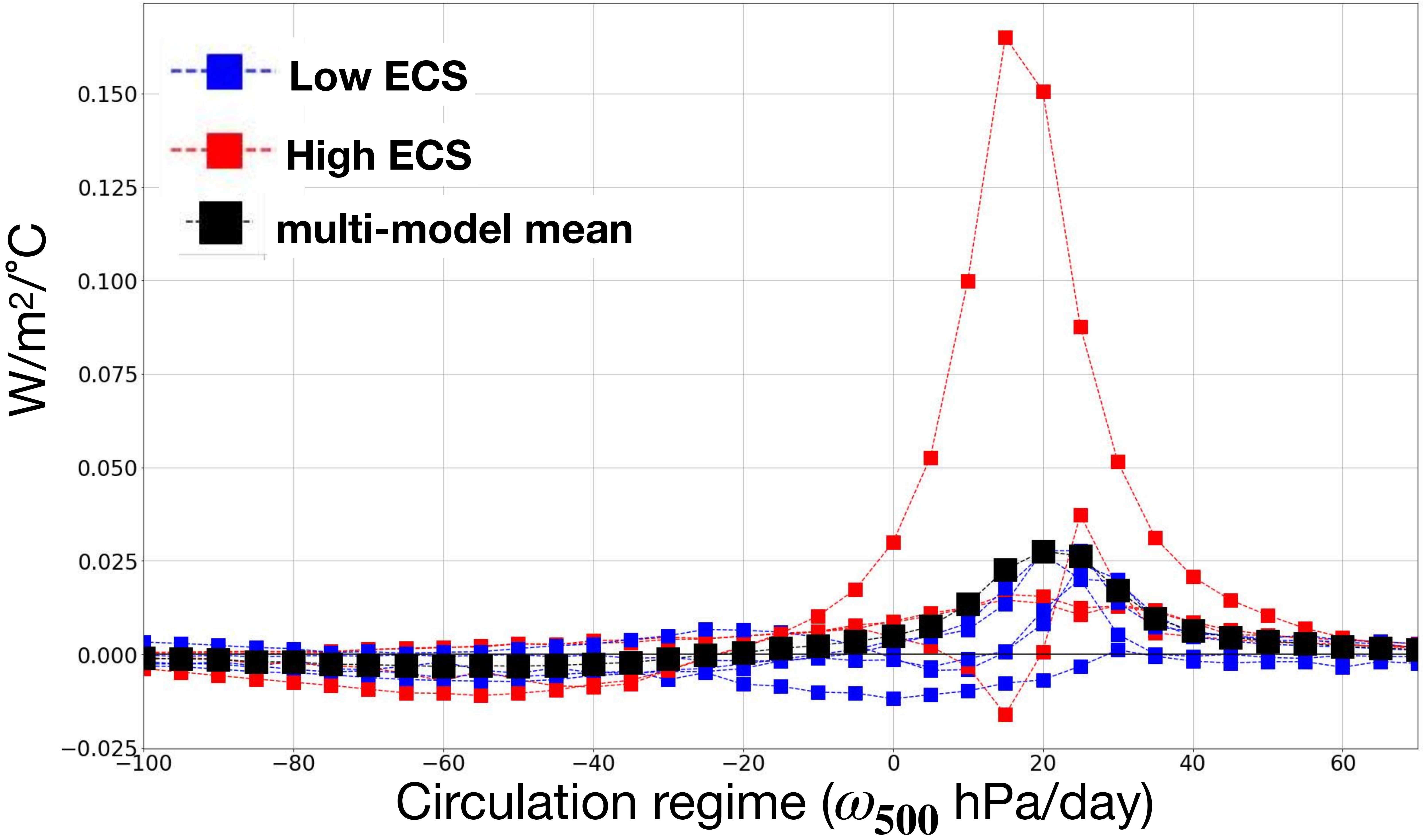


Thermodynamic contribution $P_\omega \Delta C_\omega$ to later cloud feedback

$$\overline{\delta C_\omega} = \sum_\omega C_\omega \Delta P_\omega + \sum_\omega P_\omega \Delta C_\omega + \sum_\omega \Delta P_\omega \Delta C_\omega$$

Bony et al (2004)

$\overline{\text{Y150}}$ - $\overline{\text{Y10}}$



Subsidence regimes' thermodynamic feedback most correlated with tropical cloud feedback

$$\overline{\delta C_\omega} = \sum_\omega C_\omega \Delta P_\omega + \sum_\omega P_\omega \Delta C_\omega + \sum_\omega \Delta P_\omega \Delta C_\omega$$

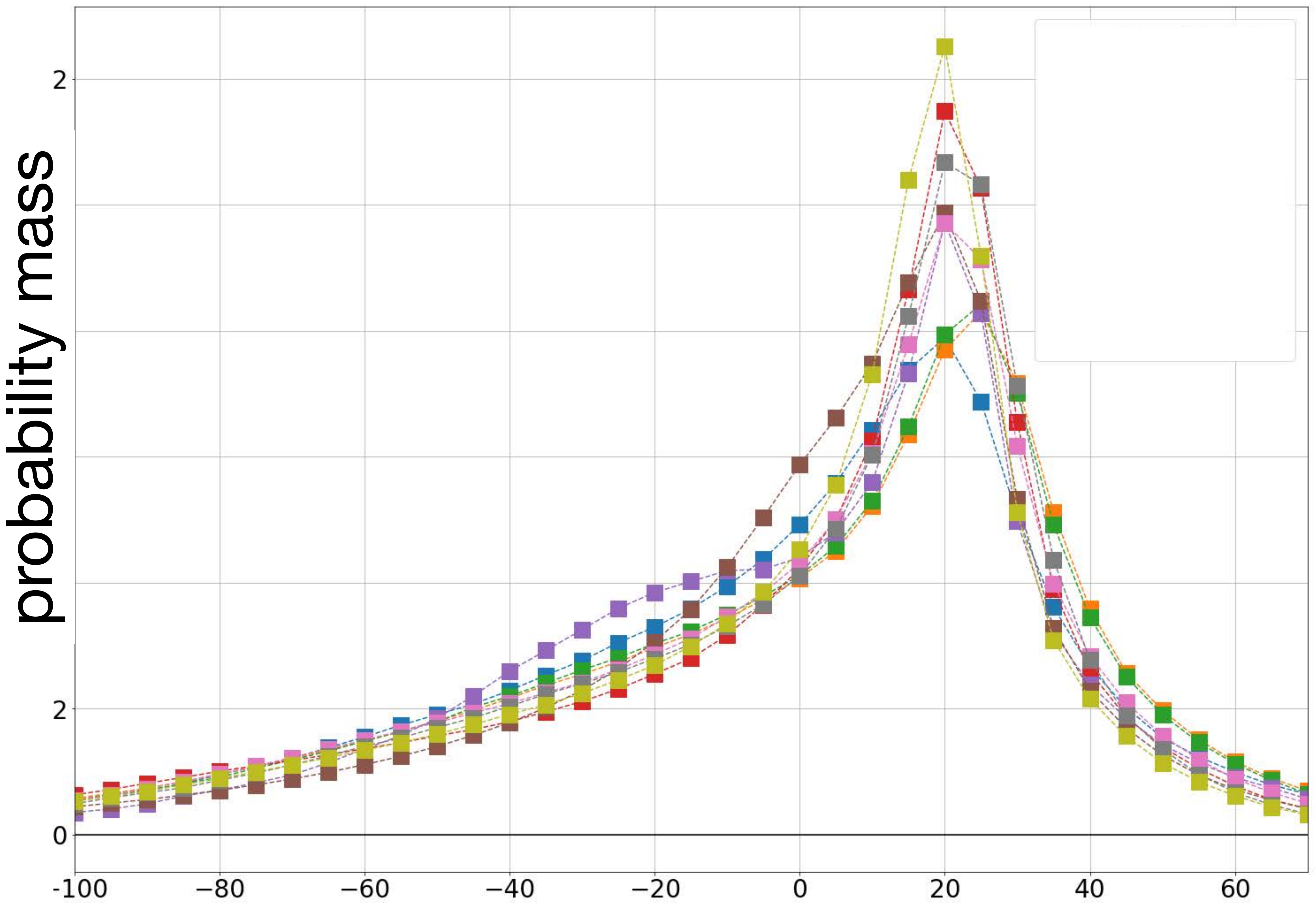
Bony et al (2004)

Thermodynamic feedback per circulation regime:

r (R^2)	Strong ascent	Weak ascent	Weak subsidence	Strong subsidence	Net
Tropical feedback	-0.40 (16%)	0.67 (45%)	0.88 (77%)	0.95 (91%)	0.92 (85%)

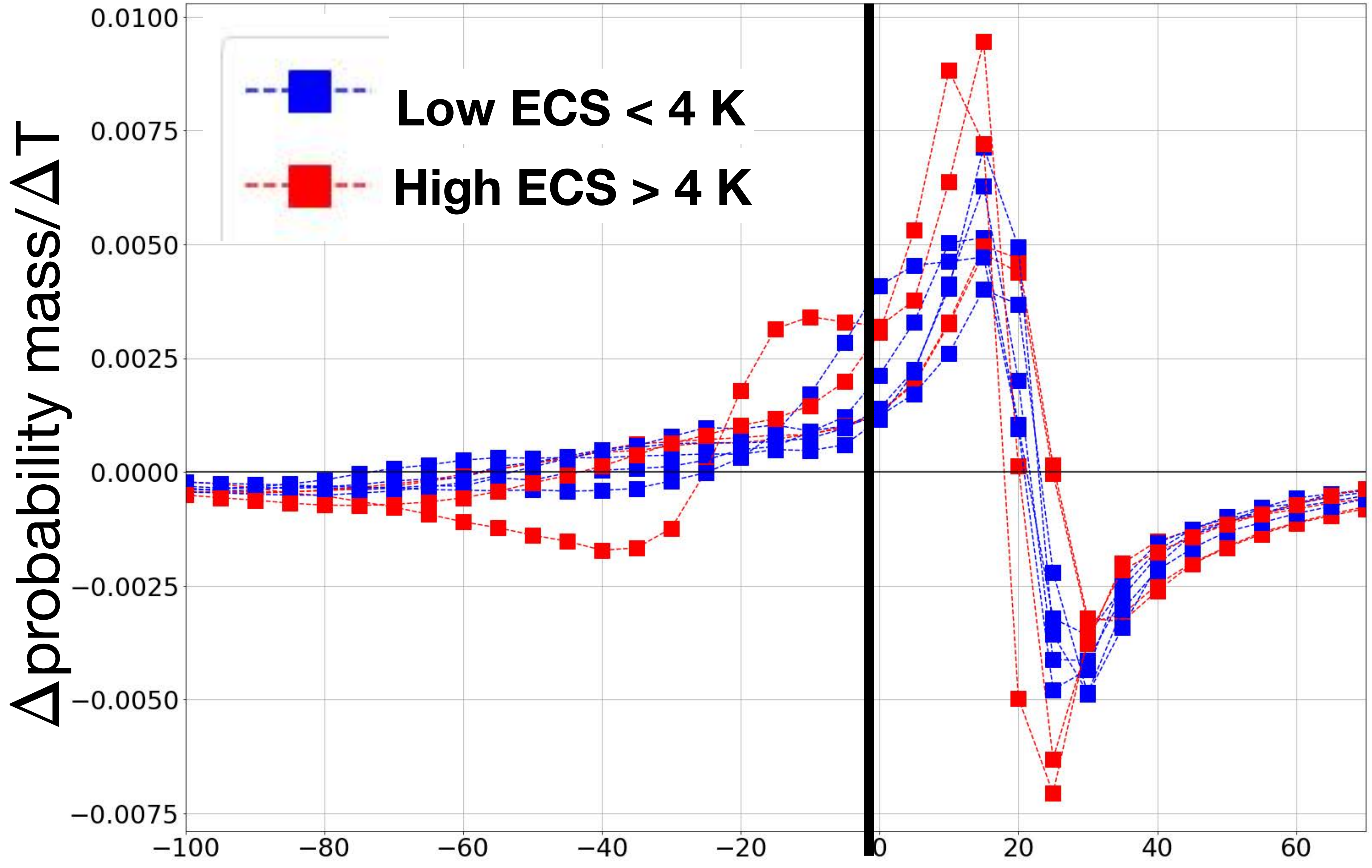
High sensitivity models associated with stronger weakening of the tropical overturning circulation

$\mathbf{P}_{\omega}$



Circulation regime (ω_{500} hPa/day)

$\delta\mathbf{P}_{\omega}$



Circulation regime (ω_{500} hPa/day)

$$I \equiv \overline{\omega}^{\downarrow} - \overline{\omega}^{\uparrow}$$

I: tropical circulation intensity (Bony et al, 2013)

ECS and dI/dT: r = -0.56 (R^2 = 32%)

Towards tropical cloud 'storylines' to discriminate between low and high sensitivity models

	Low ECS < 4K	High ECS > 4K
Initial cloud response in subsidence regimes	**-/0**	**+**
Thermodynamic cloud feedback in subsidence regions		
Weakening of the tropical circulation intensity		
SST pattern effect and EIS?		

Evaluating CMIP6 low cloud responses with EUREC^{4}A field campaign data

- EUREC^{4}A multi-platform field campaign: Jan. 20 - Feb. 20, 2020 in Barbados
  - Leverage EUREC^{4}A data to evaluate low cloud responses in CMIP6 models
  - Simple mixed-layer model to understand what controls the cloudiness in the trades, constrained with EUREC^{4}A observations

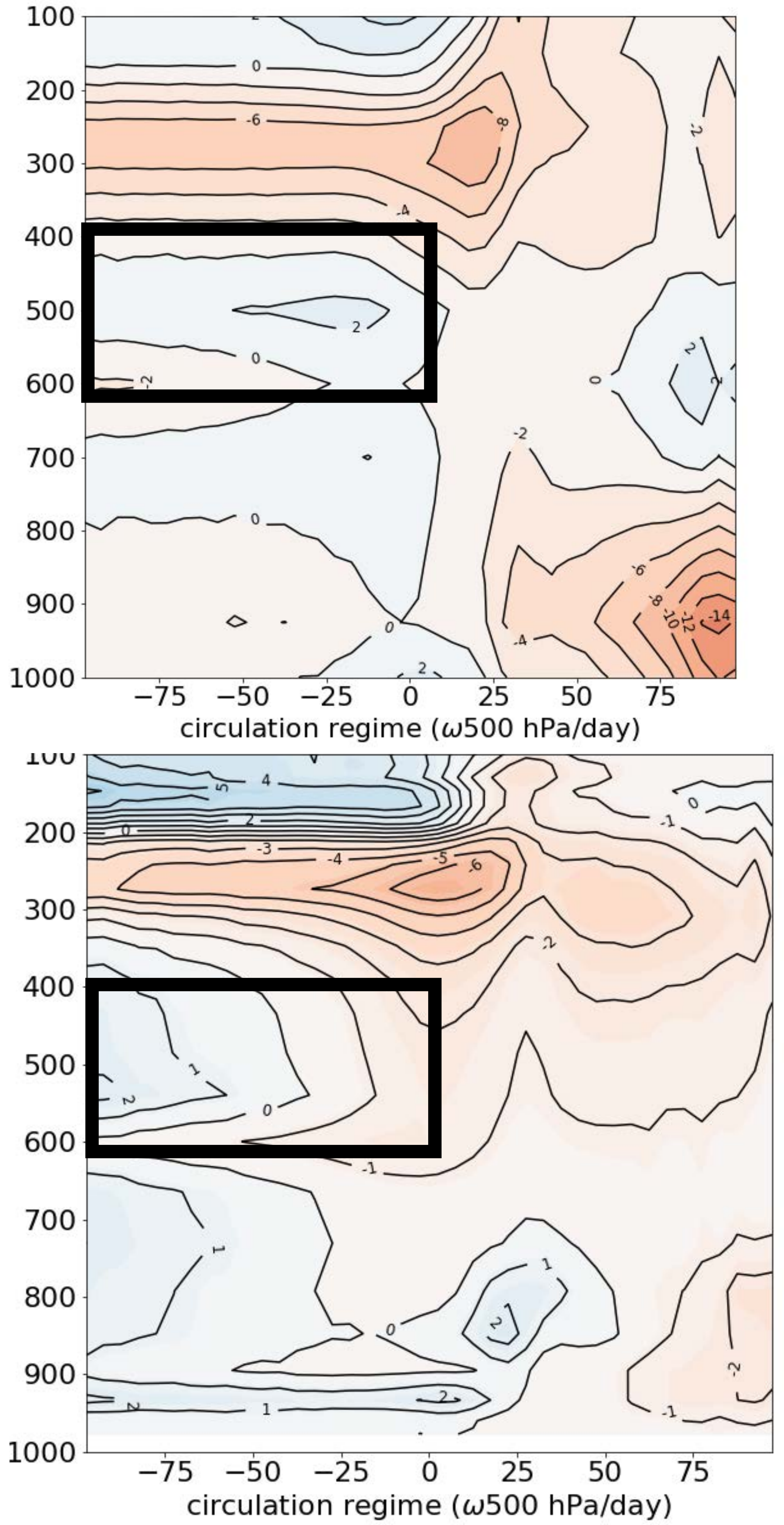
Supplementary

Greater moistening around 500hPa in ascending regions in high sensitivity models — increased cloudiness as well?

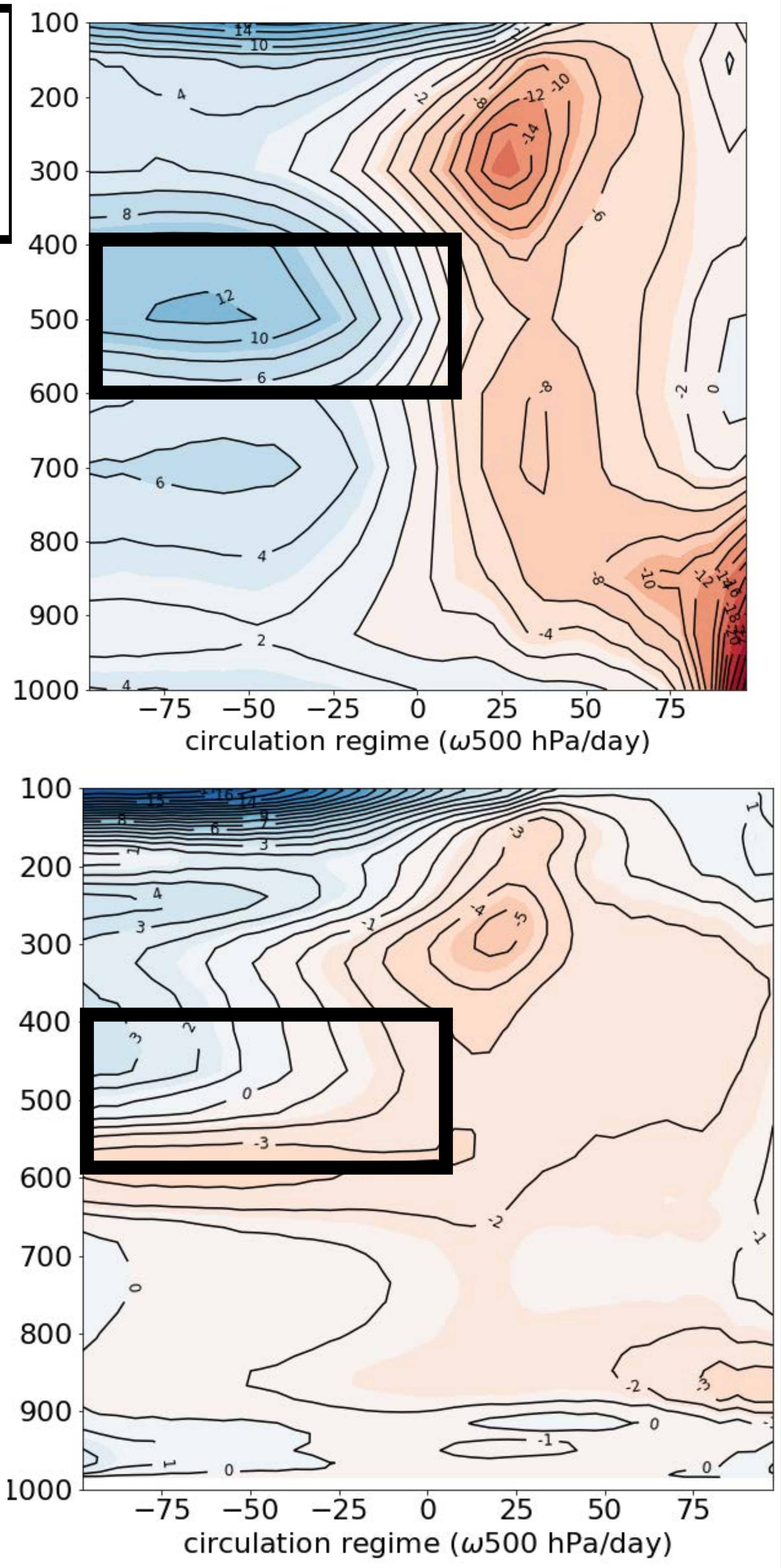
BCC-CSM Low ECS

Relative humidity anomalies (%)

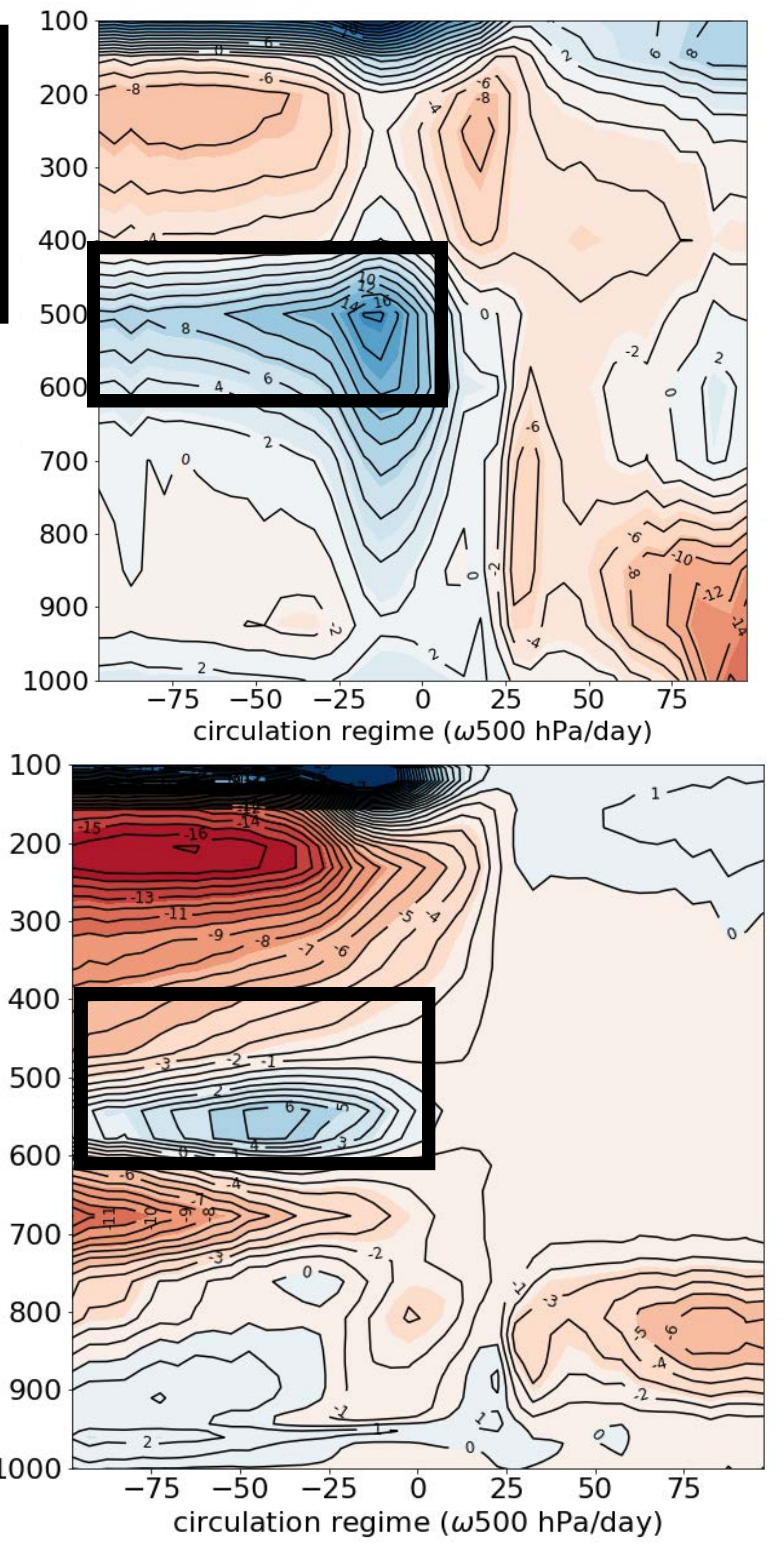
Cloud fraction anomalies (%)



CNRM-CM6 High ECS

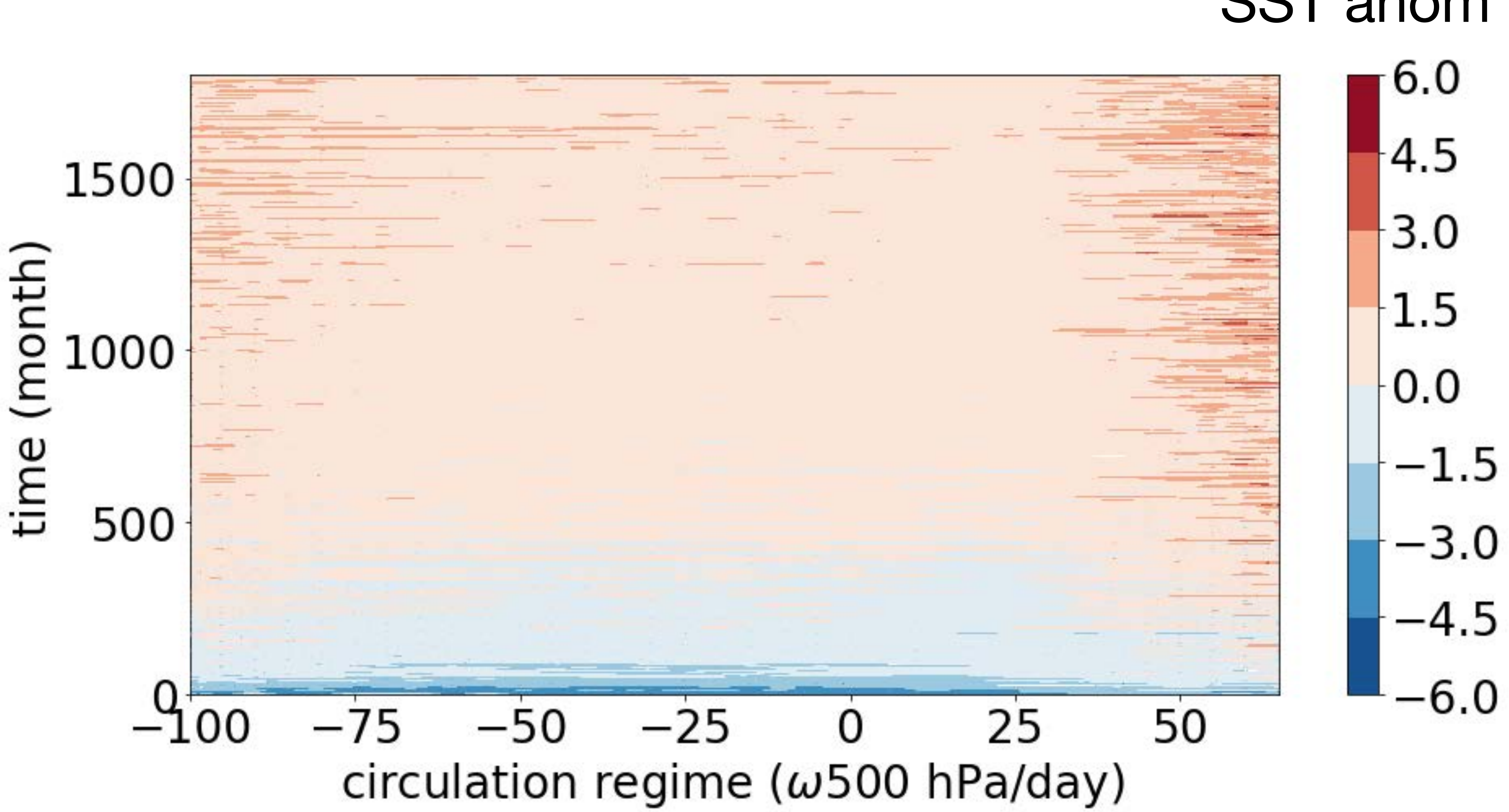


IPSL-CM6A-LR High ECS

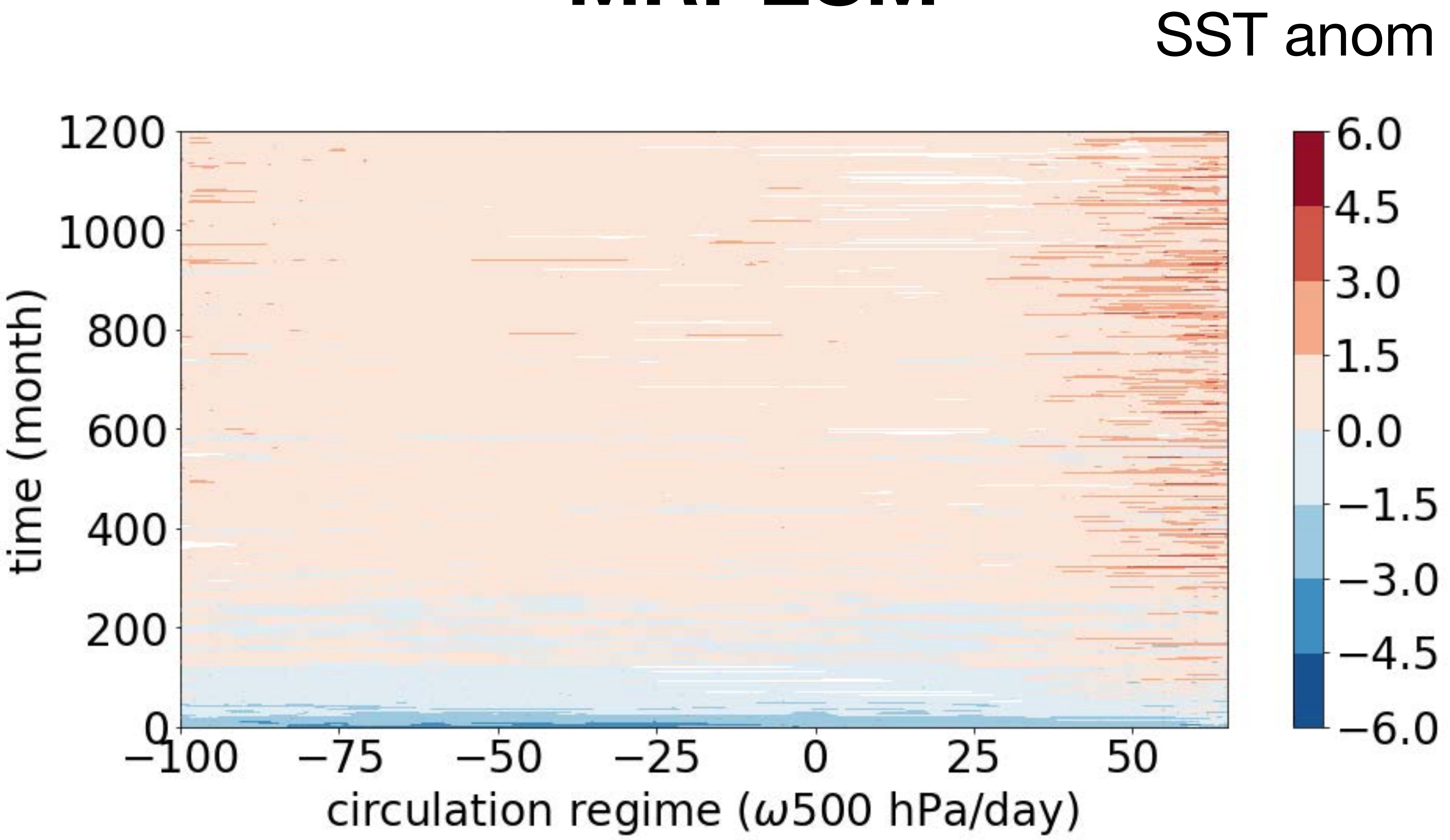


Heterogeneities in ΔSST by circulation regime?

High sensitivity model
CNRM-CM6A

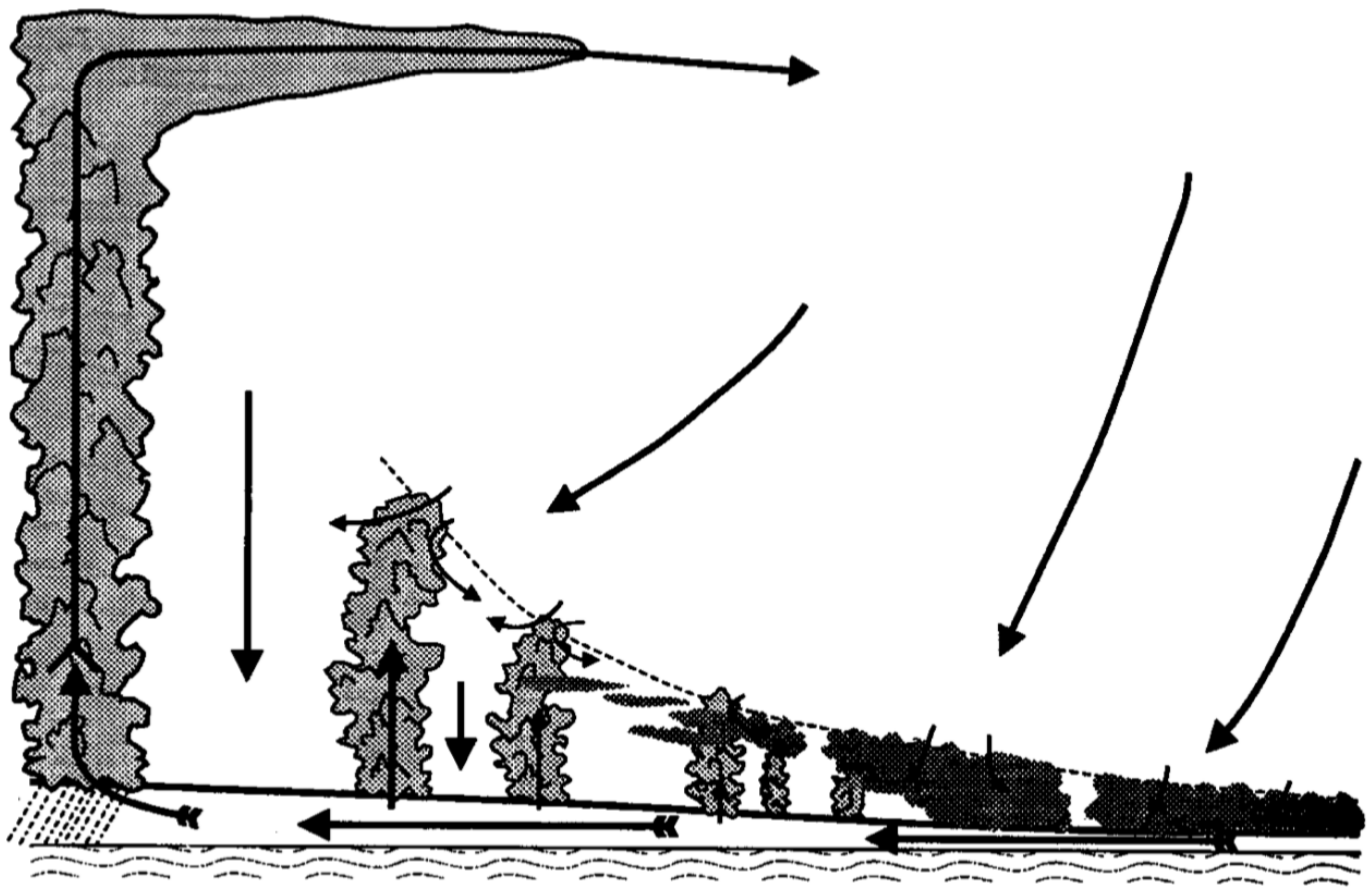


Low sensitivity model
MRI-ESM



Decompose tropical cloud feedbacks into discrete tropical circulation regimes (defined by ω_{500} hPa/day)

Tropical atmosphere



ω_{500} : Vertical velocity at 500 hPa

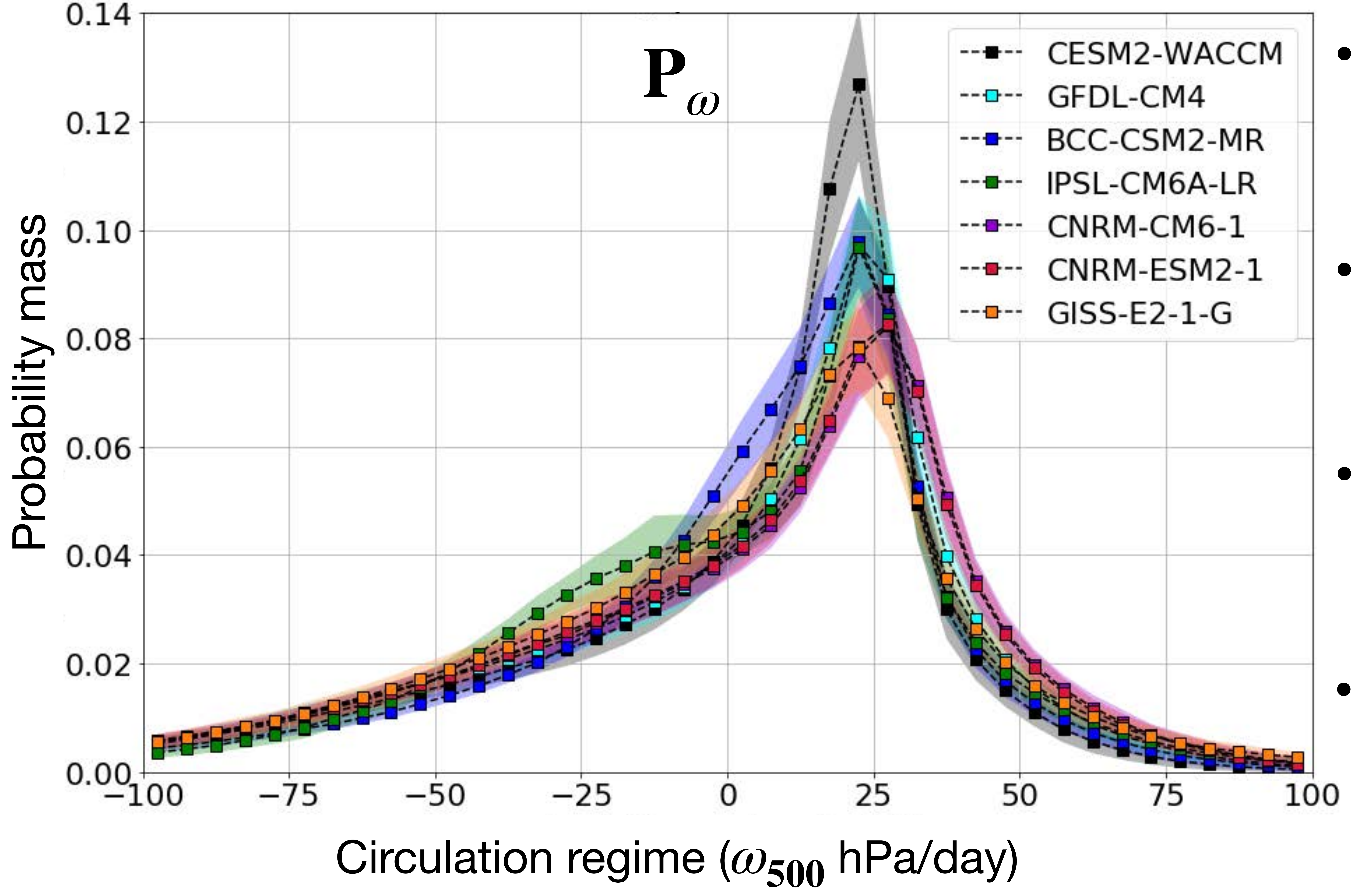
$-\omega_{500}$ ⟵⟶ $+\omega_{500}$

Large-scale ascent　　Large-scale subsidence

- ω_{500} (hPa/day), vertical pressure velocity at 500 hPa, acts as proxy for large-scale atmospheric circulation
  - Negative for ascending motions
  - Positive for subsiding motions
- ω_{500} increases with decreasing SST, moving from regions of regions of large-scale ascent (deep convection) to regions of large-scale subsidence (trade cumulus and stratocumulus regions)

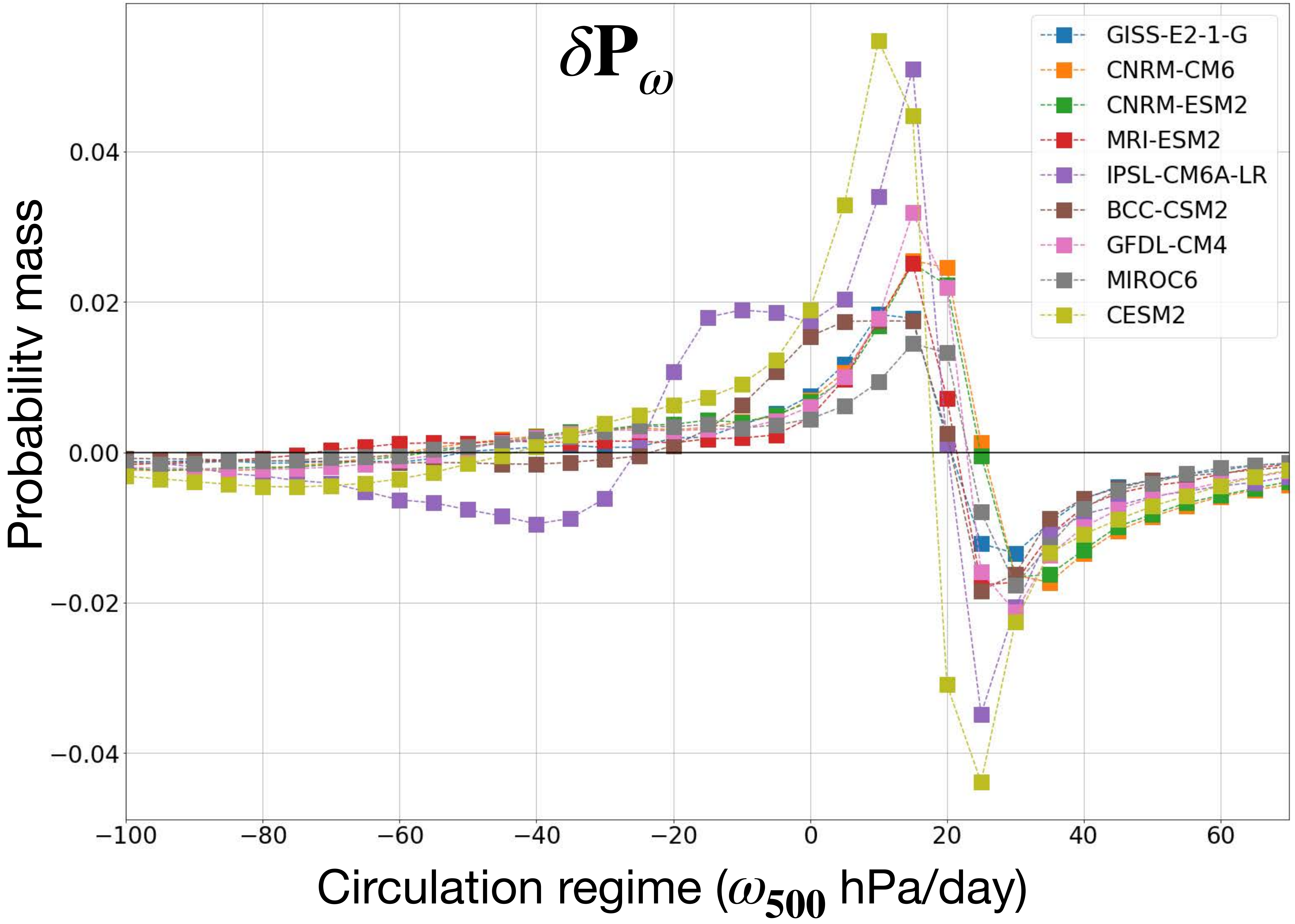
Bony, S., Dufresne, J.-L., et al. On dynamic and thermodynamic components of cloud changes. Climate Dynamics (2004) 22: 71–86

$\mathbf{P}_{\omega}$: discrete distribution of tropical circulation (pre-industrial)



- Colored shading is one standard deviation (σ) of monthly values around 20-year climatology
- Peak in distribution of in regions of weak subsidence (0-30 hPa/day), dominated by trade wind cumulus clouds
- Strength of peak in weak subsidence regimes trades off with frequency of extreme circulations
- Compare $\mathbf{P}_{\omega}$ in historical runs with ERAI $\mathbf{P}_{\omega}$

Tropical circulation changes δP_ω: abrupt4xCO_2 - piControl

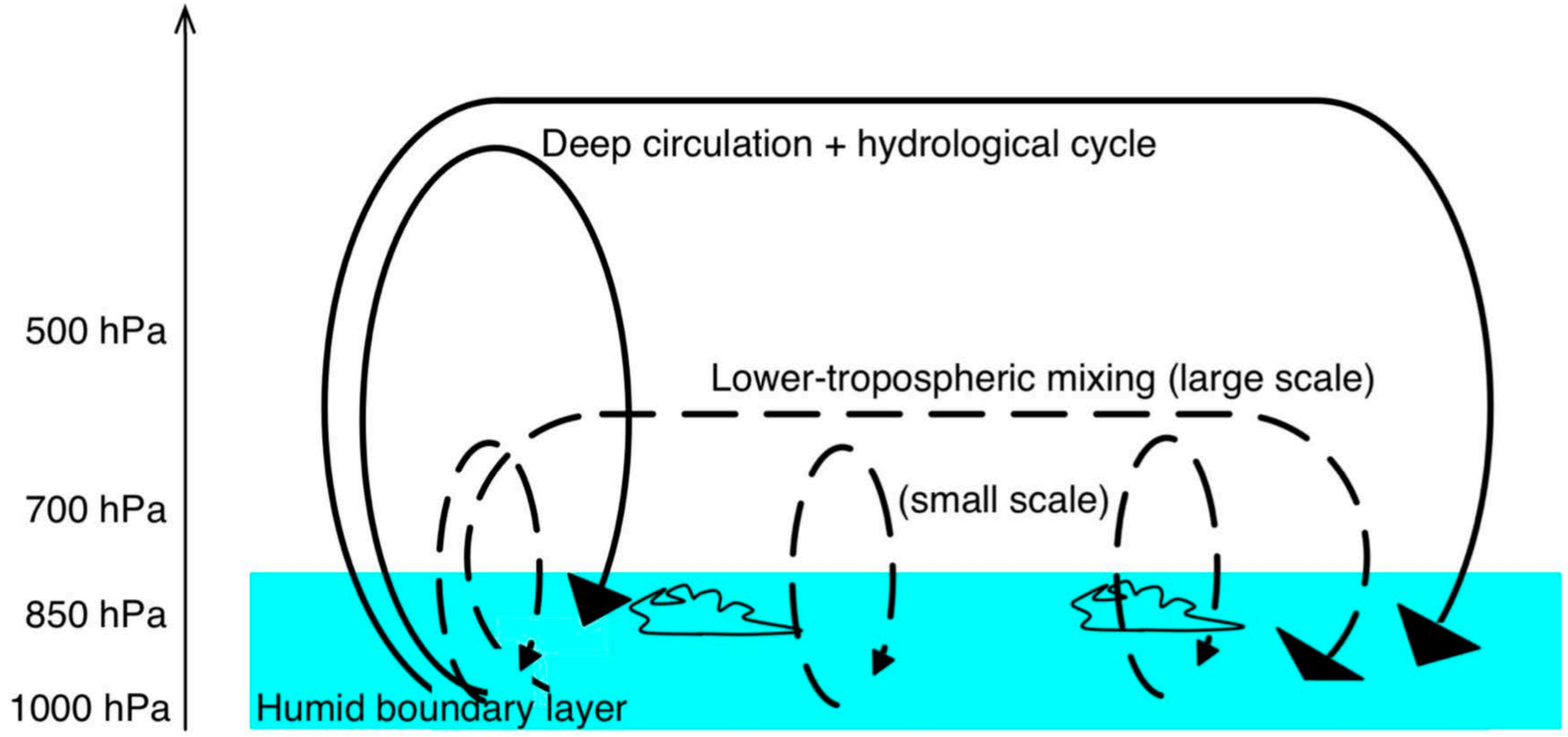


- $\delta \mathbf{P}_\omega$ illustrates the robust weakening of the tropical circulation with warming — decreased frequency of strong updrafts and strong subsidence and increased frequency of weak updrafts and weak subsidence (i.e. Vecchi and Soden, 2006)
- Demonstrates the shift in frequency towards weaker large-scale subsidence in trade wind cumulus regimes (0, 30 hPa)
- IPSL-CM6A peak in regions of weak ascent (-30, 0 hPa) might result from strong double ITCZ bias

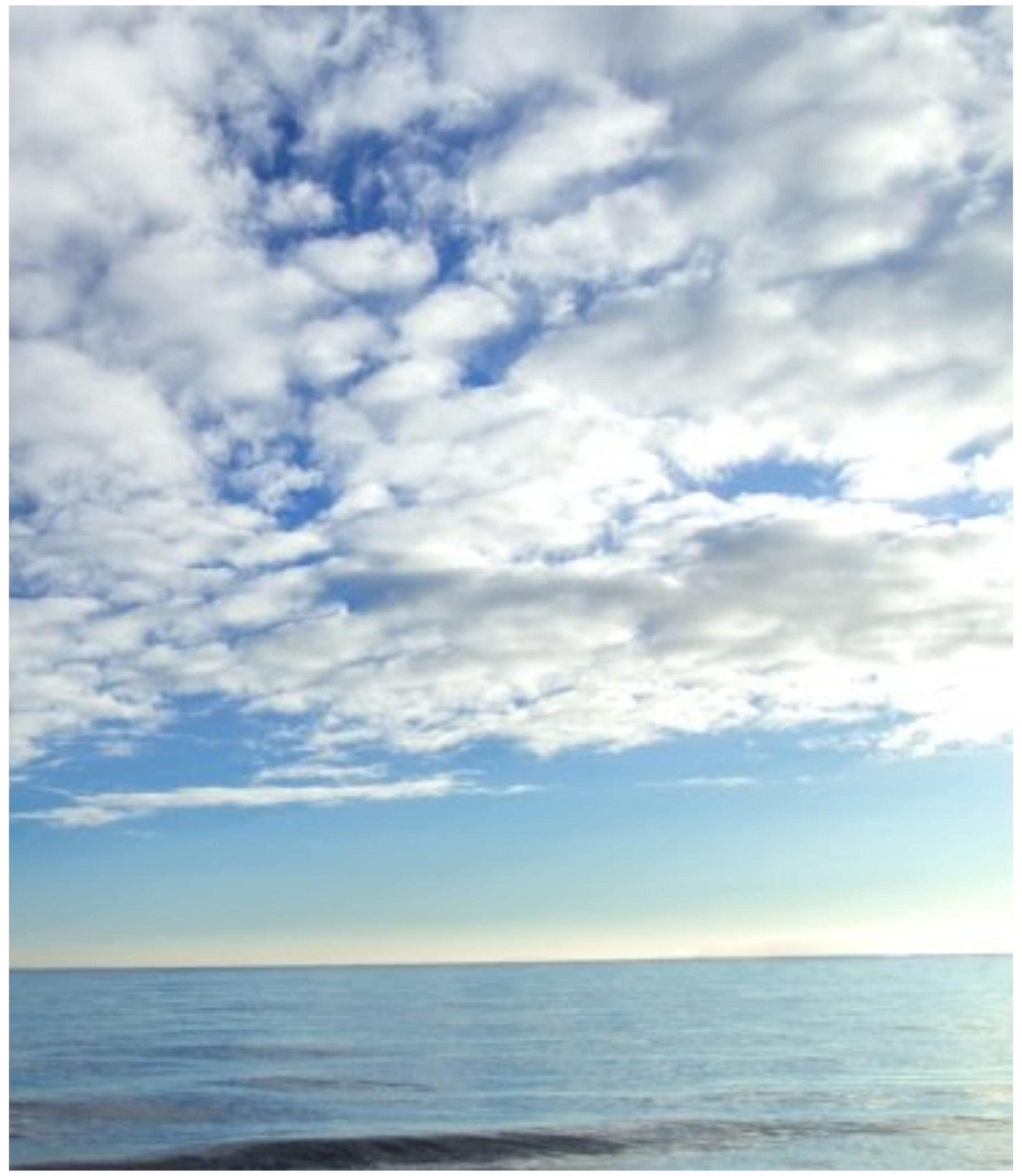
What could explain this compensatory behavior between SW and LW CRE in the tropics?

- Result of tuning?
- Two examples of possible physical mechanisms
  - ITCZ narrowing
  - Lower tropospheric mixing

Strength of lower tropospheric mixing



Sherwood et al, 2014

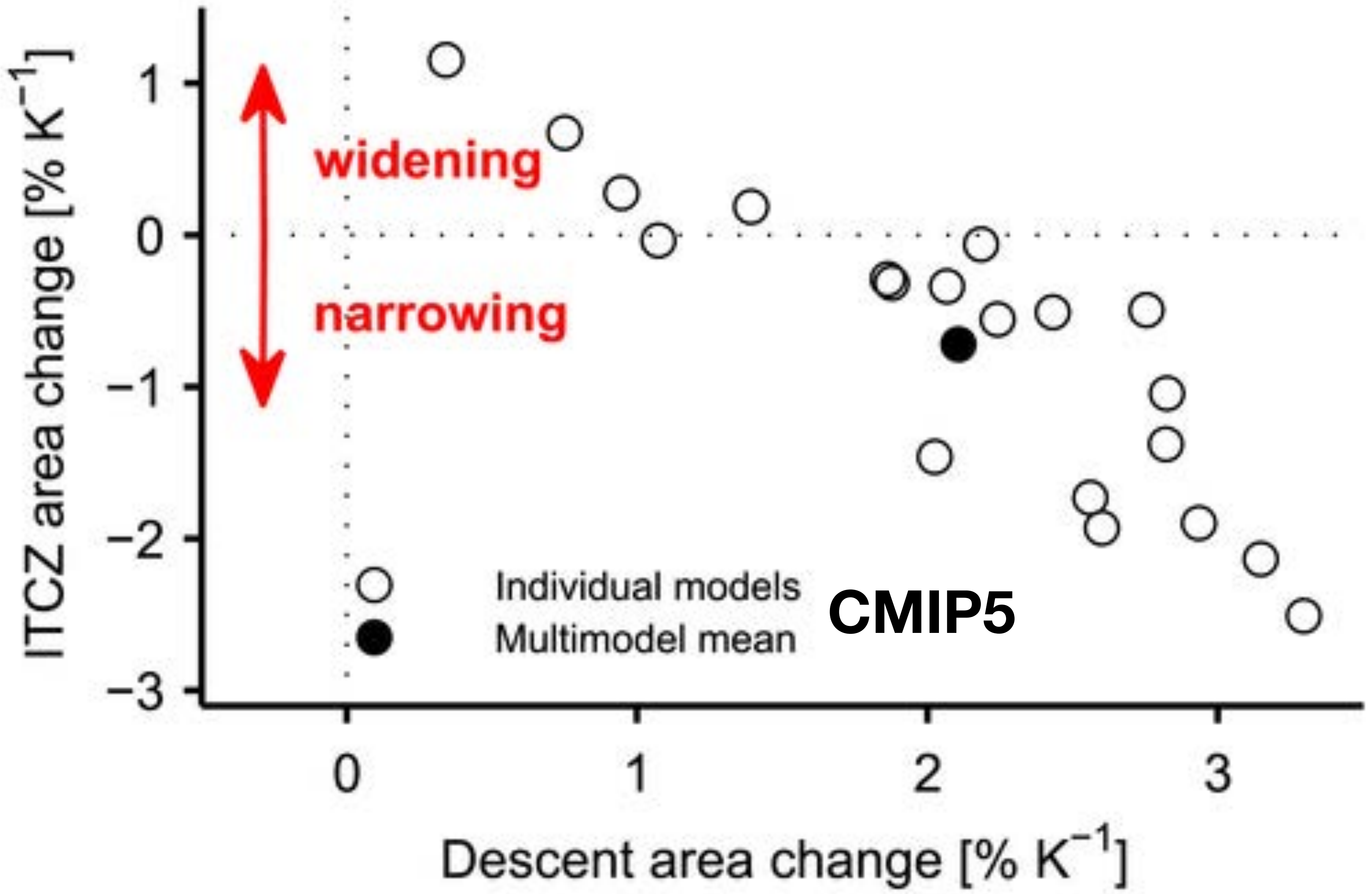


Stronger lower tropospheric mixing →

- Stronger mixing dehydrates boundary layer moisture needed to sustain low cloud cover, **positive SW CRE**

- Induces deep circulation changes? Aggregation, iris effect to have **negative LW CRE?**

ITCZ narrowing to interpret SW and LW CRE anticorrelation?



Byrne et al (2016)

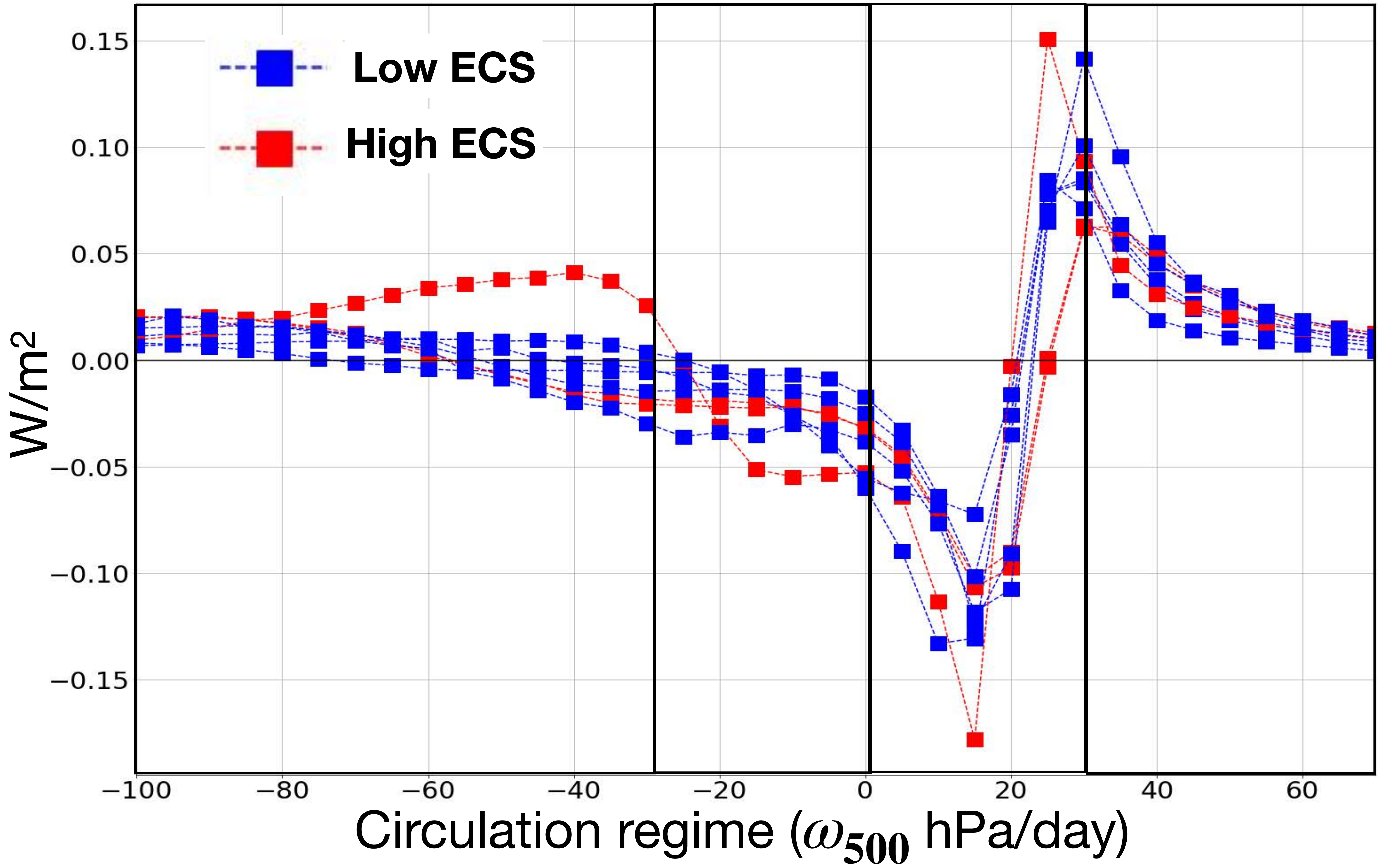
ITCZ narrows? →

- Fewer cirrus clouds, iris effect, **negative LW CRE**
- Greater low cloud fraction exposed in subsidence regimes, **positive SW CRE**

→ Test descent vs. ITCZ area changes in CMIP6 models

Correlation dynamic change $C_\omega \delta P_\omega$ and λ_c in primary circulation regimes

$$\overline{\delta C_\omega} = \sum_\omega C_\omega \Delta P_\omega + \sum_\omega P_\omega \Delta C_\omega + \sum_\omega \Delta P_\omega \Delta C_\omega$$



λ_c Net tropical cloud feedback

- Region 1 and λ_c r=0.35 (12%)
- Region 2 and λ_c r=0.08 (0.5%)
- Region 3 and λ_c r=0.48 (23%)
- Region 4 and λ_c r =-0.15 (2%)
- Dynamic component and λ_c r = 0.63 (40%)

Thermodynamic, dynamic and covariance contributions to each model's net tropical cloud feedback

Model	$\sum_{\omega} P_{\omega} \Delta C_{\omega}$ Thermodynamic	$\sum_{\omega} C_{\omega} \Delta P_{\omega}$ Dynamic	$\sum_{\omega} \Delta P_{\omega} \Delta C_{\omega}$ Covariance	= Net tropical cloud feedback
GISS-G	-0.17	-0.05	-0.004	-0.22
CNRM CM6	0.19	-0.06	-0.002	0.13
CNRM ESM	0.18	-0.07	-0.002	0.11
MRI	0.14	0.06	-0.021	0.17
IPSL	0.03	0.24	-0.012	0.26
BCC	0.06	0.04	-0.023	0.07
GFDL	0.05	0.09	-0.006	0.14
MIROC	0.01	-0.04	0.007	-0.03

Conceptual model of trade wind boundary layer

1D framework:

temperature

$$\frac{\partial \theta_{\mathrm{BL}}}{\partial t} = Q_{\mathrm{BL}} + \frac{1}{h}(w_e \Delta\theta + F_\theta) \tag{1}$$

$$\text{with} \quad \Delta\theta = \theta_0 + \Gamma h - \theta_{\mathrm{BL}} \tag{2}$$

$$F_\theta = C_{\mathrm{d}} V (\theta_{\mathrm{sfc}} - \theta_{\mathrm{BL}}) \tag{3}$$

humidity

$$\frac{\partial q_{\mathrm{BL}}}{\partial t} = \frac{1}{h}(w_e \Delta q + F_q) \tag{4}$$

$$\text{with} \quad \Delta q = q_{\mathrm{FT}} - q_{\mathrm{BL}} \tag{5}$$

$$F_q = C_{\mathrm{d}} V (q_{\mathrm{sfc}} - q_{\mathrm{BL}}) \tag{6}$$

Boundary layer height

$$\frac{\partial h}{\partial t} = w_{\mathrm{FT}} + w_e + w_m = \frac{Q_{\mathrm{FT}}}{\Gamma} + A\frac{F_{\mathrm{B}}}{\Delta\theta_{\mathrm{v}}} + w_m \tag{7}$$

$$\text{with} \quad \Delta\theta_{\mathrm{v}} = (\theta_0 + \Gamma h)(1 + \varepsilon q_{\mathrm{FT}}) - \theta_{v,\mathrm{BL}} \tag{8}$$

$$F_{\mathrm{B}} = F_\theta + \varepsilon \theta_{\mathrm{BL}} F_q \tag{9}$$

$$w_m = \begin{cases} -\frac{h-\mathrm{LCL}}{\tau} & \text{if} \quad \mathrm{LCL} < h \\ 0 & \text{if} \quad \mathrm{LCL} \geq h \end{cases} \tag{10}$$

Rapid adjustments (abrupt4xCO2 $\overline{yr.20}$ - pre-industrial mean) filtered by high and low sensitivity models and weighted by $\mathbf{P}_\omega$

Rapid adjustments * $\mathbf{P}_\omega$

Using years 0-150 of abrupt4xCO2 experiment for consistency across models

Ex. Role of time period in calculating ECS in IPSL-CM6A-LR